(54) **Measurement of distance using ultrasound**

(57) Distance measuring apparatus comprises a carrier signal generator (5), an audio-frequency modulation signal generator (6, 8, 9) to generate a modulation signal having a frequency f, and a modulator (3) to frequency-modulate the carrier signal with the modulation signal. A transmitting transducer (1) is energizable by the frequency-modulated carrier signal to transmit ultrasound energy. A receiving transducer (2) is spaced from the first point by a distance which is to be measured, and receives at least part of the transmitted ultrasound energy. A phase comparator (11) monitors the phase relationship between the audio modulation received by the receiving transducer and the transmitted audio modulation, to give a first indication (14) of the measured distance. The modulation frequency can be changed, so that finer indications (16, 18) of the distance are provided. The modulation signal generator comprises transmitting and receiving transducers (6, 8) spaced apart by a reference distance (7) and a phase-lock loop (9) to adjust the generator frequency to maintain a constant phase relationship between the transmitted and received modulation signals.
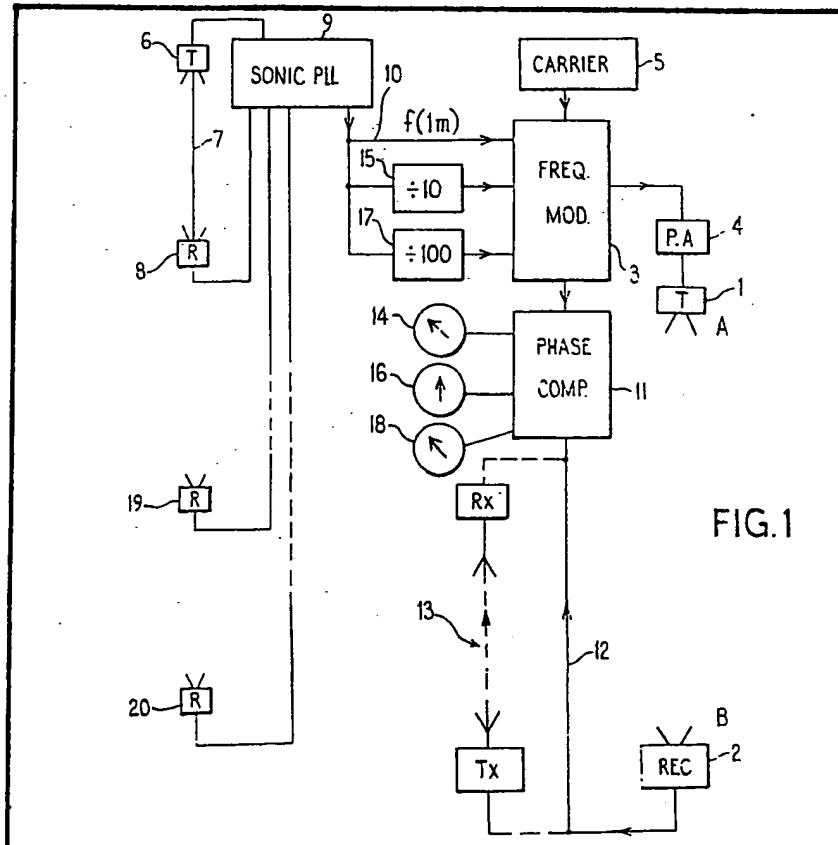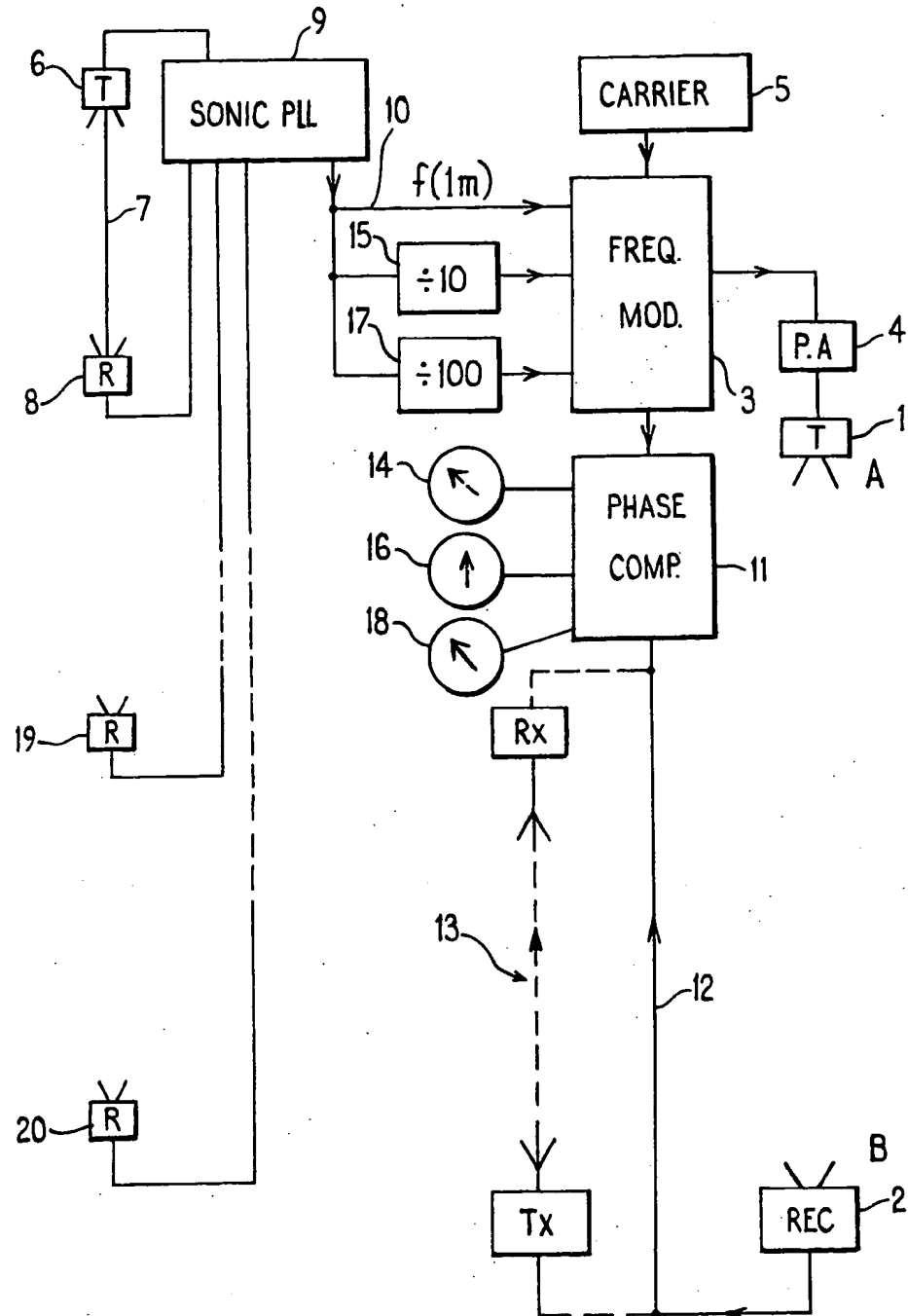
FIG.1

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FIG.1

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FIG.2

FIG.3

FIG.4

FIG.5

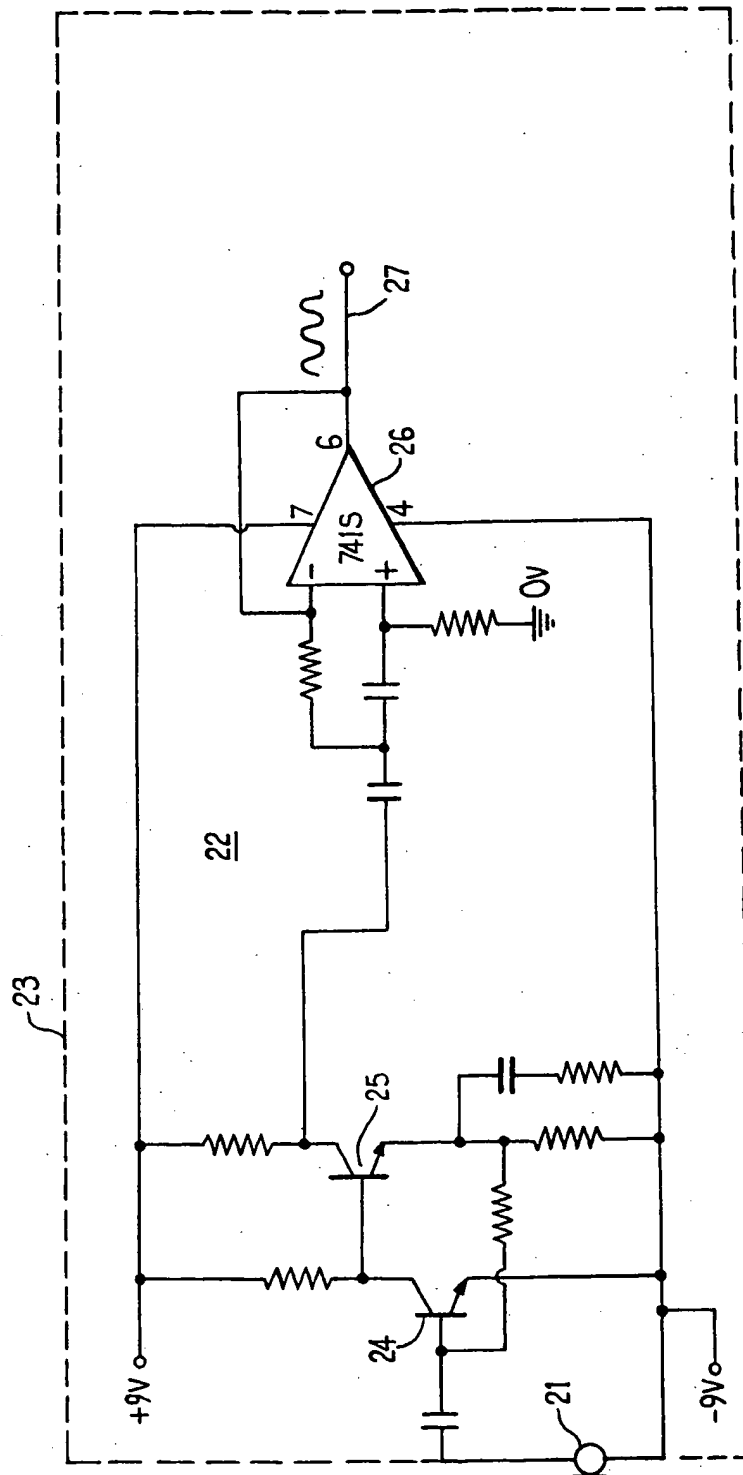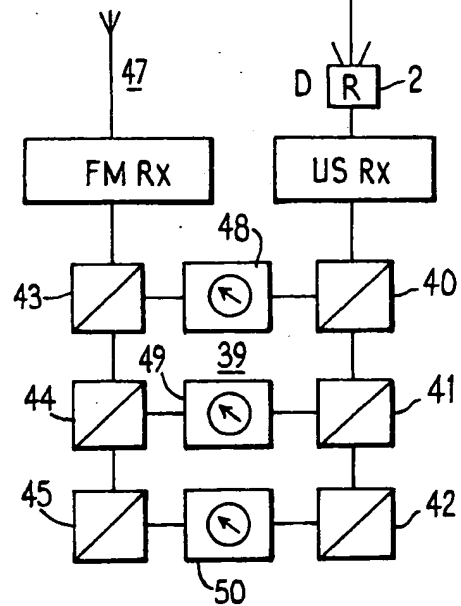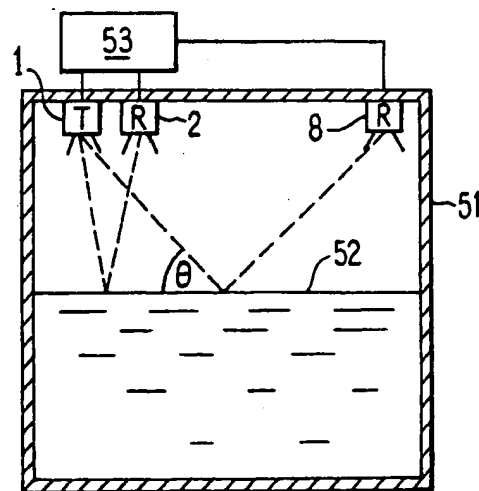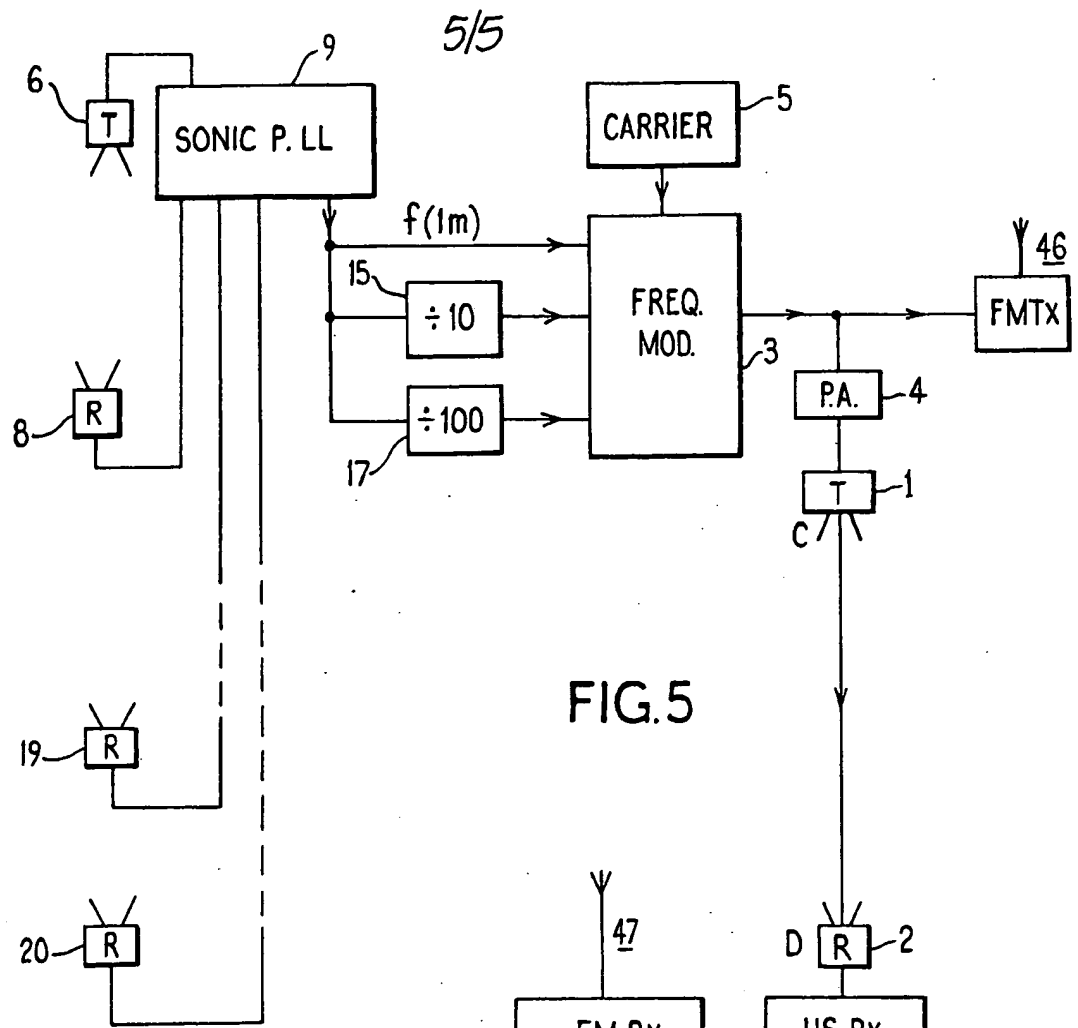

FIG.6

SPECIFICATION
Measurement of distance using ultrasound

This invention relates to apparatus for the
measurement of distance using ultrasound.
5   The use of ultrasound is well-known for
detection and ranging, and particularly for
determining the depth of the ocean or the position
of a shoal of fish or a submarine. Conventional
systems employ the emission of a sharp pulse and
10 measurement of the delay until an echo is
received back at the sending point. When such a
system is used in air, the range is very much
reduced, since the attenuation of the air is greater
than that of water and, in consequence, the
15 frequency has to be reduced to just above the
audio range. This, in turn, limits the accuracy with
which a wave front can be detected and, in
practice, ultrasound is useful only for distances
between, say, 1m and 100m in air. For
20 measurements over short distances, magnetic
and proximity devices are well established,
whereas above 100m it is usually more
convenient to use light and radio beams.
     For ranges of around 10m in air, ultrasound
25 has considerable merit, in that it is non-intrusive
and cheap, and has few physiological side-effects
and is thus superior to electro-magnetic radiation
in some circumstances.
     Apparatus for measuring distance using
30 ultrasound by a method which is far superior to
pulse emission is disclosed in my British Patent
No. 2,043,899. In that method, an ultrasound
carrier signal, frequency-modulated by an audio-
frequency signal, is fed to a transducer, and
35 resulting ultrasound energy is received at a
second transducer. The phase of the received
modulation is compared with the phase of the
transmitted modulation, and an indication of
distance is derived from the phase relationship.
40   It is an object of the present invention to
provide such an apparatus in which both coarse
and fine measurements of a distance are
produced.
     According to the present invention, distance
45 measuring apparatus comprises means to
generate an electric carrier signal; means to
generate an audio-frequency modulation signal
having a frequency f; modulator means to
frequency modulate the carrier signal with the
50 modulation signal; a first transducer located at a
first point and energizable by the frequency-
modulated carrier signal to transmit ultrasound
energy; a second transducer located at a second
point spaced from the first point by a distance
55 which is to be measured, the second transducer
being arranged to receive at least part of the
transmitted ultrasound energy; means responsive
to the phase relationship between the audio
modulation received by the second transducer
60 and the audio modulation transmitted by the first
transducer to give a first indication of said
distance; and means operable to change the
modulation signal frequency to a second
frequency f/n, where n is a positive integer,

65 whereby a finer second indication of said distance
is provided by said phase relationship responsive
means.
     The measurement of distance using ultrasound
suffers from one major drawback, namely that the
70 transmission of sound is dependent upon the
medium as regards velocity and attenuation, and
these change with the ambient conditions. For
example, the speed of sound in air is 331.46 m/s
for dry air at 0°C, and changes by 0.607 m/s per
75 °C. There are also minor changes with humidity
and pressure and variations in carbon dioxide
content. Some form of compensation for the
speed of sound is therefore necessary in many
cases.
80   One obvious way of compensating is to
measure the temperature and to allow for its
variations in the time/distance conversion factor.
This is, however, only approximate, since the
temperature will be read at one point only.
85   A better method is to use a comparator
technique involving a reference distance, as often
adopted in pulse-echo system. A small target,
often in the form of a pin, fixed a short distance in
front of the sensor is employed to give a reading
90 representing a known reference distance.
However, the reference distance in practical
circumstances must be shorter than the working
range; in measuring the depth of a liquid in a tank
it is usually limited to the dead space above the
95 high level mark. Consequently, as the level falls,
the reference becomes a decreasing fraction of
the measured path and any variations beyond the
reference distance will not be compensated.
Since the temperature and vapour content
100 adjacent to the liquid may well be different from
that near the datum, the compensation depends
on the extent to which the reference distance
conditions represent the actual path. This
imposes a basic limitation on the finite accuracy
105 capability of the system.
     In the case of pulse echo systems, and
particularly in systems in which the same
transducer is used for transmission and reception
of pulses, there seems little that can be done to
110 make a short reference distance more
representative of the ambient conditions. It
appears, at first sight, that a continuous wave
system can be improved by pointing a reference
transducer downwards to recieve reflections from
115 the surface of the liquid so that a bigger part of
the total path is traversed by both beams.
However, there seems inherently to be no
advantage, since the reference is still the short
distance in the dead volume at the top of the tank.
120   A preferred embodiment of the present
invention, by means of which the depth of a liquid
is measured, provides improved compensation for
the ambient conditions.
     Embodiments of the invention will now be
125 described, by way of example, with reference to
the accompanying drawings, in which:
     Fig. 1 is a block schematic diagram of a first
form of distance measuring apparatus in
accordance with the invention,

Figs. 2 and 3 together form a block schematic diagram of a carrier signal control circuit and a transmitter circuit of the apparatus of Fig. 1,

Fig. 4 is a block schematic diagram of a
5 preamplifier and filter circuit for use with a particular type of receiving transducer in the circuit of Figs. 2 and 3,

Fig. 5 is a block schematic diagram of an alternative distance measuring apparatus in
10 accordance with the invention, and

Fig. 6 is a block schematic diagram of a liquid level measuring apparatus in accordance with the invention.

Referring to Fig. 1 of the drawings, apparatus
15 for measuring the distance between two points A and B comprises a transmitting transducer 1 located at the point A and a receiving transducer located at the point B. The transducer 1 is fed with a frequency-modulated carrier signal from a
20 modulator 3, via a power amplifier 4. The carrier signal is provided by a circuit 5, which will be described in detail later.

In order to determine a suitable modulation frequency, a reference transmitting transducer 6
25 transmits over a reference distance 7 through the atmosphere in which the measurement is to be made. The reference distance 7 may, for example, be 1 metre. The transmitted wave is received by a receiving transducer 8, and a phase-lock loop 9,
30 to which the transducers 6 and 8 are connected, sets the frequency f of the transmitted wave such that it is resonant for the selected reference distance in the prevailing ambient conditions.

The signal at the frequency f set by the phase-
35 lock loop 9 is fed to the modulator 3 over a line 10, to act as the modulating frequency.

The frequency-modulated carrier signal fed to the transducer 1 causes the transducer to transmit a frequency-modulated ultrasound wave,
40 at least part of which is received by the receiving transducer 2. The signal from the transducer 2 is fed to a phase comparator 11 via a wire link 12 or a radio link 13.

The phase of the received modulation is
45 compared with the phase of the transmitted modulation by the comparator 11, and the phase relationship gives a measure of the distance AB as compared with the reference distance 7. The distance is indicated on a meter 14 which is
50 connected to the comparator. However, this meter can only indicate the phase displacement of one cycle of the received modulation; it cannot indicate the number of complete wavelengths between the points A and B. If, now, the
55 frequency f is divided by 10 in a divider circuit 15, and the resulting frequency is used to modulate the carrier, a different phase relationship will result, and this will be indicated on a corresponding meter 16, giving a finer distance
60 measurement. The frequency f is also divided by 100 in a divider circuit 17, and a further indication is given on a meter 18. It is not essential to use ÷10 and ÷100 circuits; other divisors could be used, depending upon, for example, the maximum
65 range of distances envisaged.

Instead of dividing the basic reference frequency f, using dividers 15 and 17, separate reference transducers 19 and 20 spaced 10 times and 100 times as far from the transmitting
70 transducer 6 as the transducer 8 could be used. The resulting resonant frequencies set up by the phase-lock loop 9 would be substantially f/10 and f/100, respectively, but this would, in fact, improve the performance of the apparatus
75 because the references would be more representative of any non-uniformities within the path. If the reference is longer than the path over which the measurement is being made, then the compensation for temperature and other velocity
80 effects is virtually complete, since the performance is only related to the sensitivity of the system. Because the system is fully electronic, errors due to deadzones and hysteresis are eliminated. The main limitations on the
85 performance are a function of the noise in the received signal due to random variations. In this connection it is worth noting that the continuous wave system is far superior to the pulse-echo type of operation because the latter provides periodic
90 results following pulsing of the system for short intervals of time, whereas the present system, in which continuous monitoring of phase is carried out, gives a result which follows all the random and ambient changes occurring in the
95 measurement path. A pulse system will give a number of spot readings, and even if many readings are taken and averaged the result could still be inaccurate due to "aliasing". On the other hand, the present continuous system shows a
100 reading on a meter which endeavours to follow all of the excursions. If the indicating device is a pointer and dial instrument with suitable damping, it is easy to judge the noise in the system at all times and to estimate visually the
105 average figure.

The apparatus is very versatile and can be adapted to circumstances. For example, one carrier signal could carry at least three measuring waves as modulation, their separation being
110 achieved by filters at the receiving end, or the measuring waves could be sent as three separate modulated carrier signals of different frequencies. In fact, these carrier frequencies could be at variable or fixed values which are suitable for the
115 distances at which it is required to receive the particular wave.

The carrier frequency is in no way critical to the operation of the sonic phase-locked loop. The carrier is chosen to suit the characteristics of the
120 transducer, while being high enough to ensure that there is adequate attenuation in the path to enhance the well-known FM single-signal capture effect. For measurement purposes, the ideal carrier frequency is the highest one at which a
125 just-limiting signal is received by the receiving transducer, since this means that the path has minimum energy input and minimum disturbance. However, this requires the use of broadband transducers, whereas most piezo-ceramic units
130 and crystals are resonant. Fortunately, in the area

where the present invention is especially
applicable, namely for distance measurement in a
range of 1—100m in air, the carrier wave has to
be below about 50kHz, and audio devices are
5 available which will operate satisfactorily at such
frequencies. In particular, the tweeter loud
speaker and the electret microphone are capable
of operation well above the audio range. As an
example, a miniature microphone as used in
10 hearing aids can operate up to about 160kHz, and
it is usually necessary to cut the response
deliberately in an amplifier which is fed by the
microphone.
    A circuit for use with such a microphone is
15 shown in Fig. 4 of the drawings. In that figure, the
microphone 21 is connected to the input of an
amplifier and filter circuit 22, preferably contained
within a screening box 23. The amplifier section
of the circuit comprises transistors 24 and 25 and
20 associated components connected in a
conventional circuit. The filter section comprises
an operational amplifier 26 and associated
components arranged to give, for example, a roll-
off characteristic below 10kHz. The output of the
25 circuit is fed to a line 27 for connection to the
circuit of Fig. 2.
    An alternative to such microphone and filter
combination is a sonic transducer of the wide
band non-resonant type comprising a metalised
30 film caused to vibrate by capacitive electro-static
action. However, such transducers require a
polarising voltage. In certain models, for example
the AKG 3020 unit, the response is naturally quite
poor below about 15kHz but is adequately linear
35 up to at least 60kHz.
    As mentioned previously, the carrier frequency
is selected such that it is the highest frequency
which gives an adequate signal along the
measurement path. This selection is achieved by
40 the circuitry shown in Figs. 2 and 3.
    Referring, firstly, to Fig. 3, the carrier signal is
generated by a voltage-controlled oscillator 28
which produces a pulse train having a repetition
frequency which is dependent upon the voltage
45 applied to an input 29. The pulse train is fed to an
amplifying transistor 30 and thence via a power
amplifier comprising complementary transistors
31 and 32 to the transmitting transducer 1.
    Referring to Fig. 2, the resultant ultrasound
50 energy reaches the receiving transducer 2. That
transducer may comprise the whole of the circuit
of Fig. 4 as described above, or may be any other
suitable transducer. The carrier signal is fed to an
IF and demodulator circuit 33 which outputs the
55 modulation signal on a line 34 for phase
comparison with the transmitted modulation as
explained above. The carrier is also fed to an
AC/DC converter 35 which determines the
average value of the carrier amplitude and feeds a
60 signal representing that value to an integrator 36
having a long time constant. The output of the
integrator is a voltage varying from —1.25 volts to
—1.75 volts depending upon the frequency of the
carrier signal. That voltage is fed to an offset-
65 determining circuit 37 which can be adjusted to

set the upper and lower limits of the resultant
frequency control voltage which it feeds to a line
38 and thence to the control input 29 of the
oscillator 28. With the particular oscillator used,
70 an upper limit control voltage of 9.8 volts
produces a frequency of 15kHz and a lower limit
voltage produces a frequency of 52kHz.
    When the apparatus is in use, the integrator
will gradually increase the negative voltage,
75 thereby reducing the VCO control voltage. The
carrier frequency will therefore increase, and this
will continue until such time as the attenuation in
the ultrasound path causes a reduction in the
amplitude of the received carrier at the input of
80 the converter 35. The control voltage then
increases, thereby reducing the carrier frequency.
The carrier frequency therefore sets at the highest
level which will produce an adequate signal at the
converter 35, despite the attenuation in the path.
85   The modulation signal is fed to the control
input 29 of the VCO 28 from the phase-lock loop
9 or from the divider 15 or 17 of Fig. 1, as the
case may be.
    An alternative arrangement is shown in Fig. 5
90 in which the same components as used in Fig. 1
have the same reference numerals. In this case,
the receiving transducer 2 is contained in a
portable unit 39, which also contains audio filters
40—42 for separating the three modulation
95 frequencies (f, f/10, f/100), and phase
comparators 43—45. The transmitted
modulation is also fed over an FM radio link 46,
47 to the phase comparators 43—45 for
comparison with the received modulation phase.
100 The phase relationships, and hence the distance
measurements, are indicated on meters 48—50.
    The transmitter can therefore act as a beacon
at a location C, and the portable unit 39 can be
pointed at the beacon whilst held at any location
105 D within range of the beacon. The distance CD
can then be read off. Again, the frequency dividers
may be dispensed with and further reference
transducers 19 and 20 used as in Fig. 1.
    Two such systems could be employed with the
110 two transmitting transducers pointing in mutually
perpendicular directions and located at the
centres of adjacent sides of a square. A portable
receiver unit could then determine its exact
position within the square. Such a system could
115 be used for controlling the position of a robot.
    Three-dimenstional operation would also be
possible by employing three transmitter systems
in which the transducers face in mutually
perpendicular directions. To avoid ambiguity, the
120 three systems could have different carrier
frequencies so that each axis could be tuned-in in
turn at the receiving point, or three receivers
could be used.
    Although the above embodiments have been
125 described in relation to air, the apparatus could
also be used in any sound transmitting medium.
For example, it could be used in water, for
navigation or for the control of diving.
    Fig. 6 illustrates the use of apparatus in
130 accordance with the invention for determining

the depth of liquid in a tank 51 by measuring the
distance between the surface 52 of the liquid and
the top of the tank. In this case, the transducers 1
and 2 are located at the top of the tank pointing
5 downwards, and the transducer 2 receives the
ultrasonic beam after reflection from the surface
of the liquid. The result of the measurement is,
therefore, always twice the actual distance which
is being measured. The components 3, 4, 5, 9, 10,
10 11 and 14 (and 15—18, if required) of Fig. 1 are
contained in a unit 53. The reference receiving
transducer 8 is located at the top of the tank,
displaced from the transducer 1 by a reference
distance which is as large as convenient. In this
15 embodiment the transducer 8 also receives its
signal from the transducer 1 instead of a separate
transmitting transducer being used for the
reference path. The respective transit times from
the transmitting transducer 1 to the surface 52
20 and thence to the two receiving transducers 2 and
8 are measured. The difference between these
two times varies as the sine of the angle θ
between the second beam path and the surface,
because of the displacement of the second
25 transducer by the reference distance. This
appears to give complete compensation for
ambient conditions, provided that any
temperature or vapour concentration gradients
are uniform, which seems very likely in the case of
30 an air space.
This triangulation method of compensation in
which the reference receiving transducer is
spaced an appreciable horizontal distance from
the transmitting transducer is far better than the
35 conventional target-pin method mentioned above.
The type of apparatus used in the Fig. 6
embodiment, in which the transducers all face
towards a surface so that the receiving
transducers receive ultrasound transmissions
40 after reflection from the surface, and in which the
reference distance is measured along the plane in
which the transducers are located, may be used
for other measurements besides the
measurement of liquid level in a tank.

45 **Claims**
1. Distance measuring apparatus, comprising
means to generate an electric carrier signal;
means to generate an audio-frequency
modulation signal having a frequency f; modulator
50 means to frequency modulate the carrier signal
with the modulation signal; a first transducer
located at a first point and energizable by the
frequency-modulated carrier signal to transmit
ultrasound energy; a second transducer located at
55 a second point spaced from the first point by a
distance which is to be measured, the second
transducer being arranged to receive at least part
of the transmitted ultrasound energy; means
responsive to the phase relationship between the
60 audio modulation received by the second
transducer and the audio modulation transmitted
by the first transducer to give a first indication of

said distance; and means operable to change the
modulation signal frequency to a second
65 frequency f/n, where n is a positive integer,
whereby a finer second indication of said
distance is provided by said phase relationship
responsive means.
2. Apparatus as claimed in Claim 1, wherein
70 the means operable to change the modulation
signal frequency is further operable to change
that frequency to f/m, where m is a positive
integer larger than n, whereby a third indication,
finer than said second indication, is provided by
75 the phase relationship responsive means.
3. Apparatus as claimed in Claim 1 or Claim 2,
further comprising a first reference receiving
transducer spaced by a reference distance from a
reference transmitting transducer, the reference
80 transducers being connected in a phase-lock loop
circuit which sets the modulation frequency f in
dependence upon the reference distance and the
ambient conditions in the path between the
reference transducers.
85 4. Apparatus as claimed in Claim 3, further
comprising a second reference receiving
transducer spaced from the reference
transmitting transducer by a distance n times the
reference distance of said first reference receiving
90 transducer, whereby the phase-lock loop can set
the modulation frequency at f/n.
5. Apparatus as claimed in Claim 4, further
comprising a third reference receiving transducer
spaced from the reference transmitting
95 transducer by a distance m times the reference
distance of said first reference receiving
transducer, m being a positive integer larger than
n, whereby the phase-lock loop can set the
modulation frequency at f/m.
100 6. Apparatus as claimed in any preceding
claim, further comprising a radio link between the
second transducer and the phase relationship
responsive means for communicating to said
responsive means the phase of the received audio
105 modulation.
7. Apparatus as claimed in any one of Claims
1—5, further comprising a radio link between the
modulator means and the phase relationship
responsive means for communicating to said
110 responsive means the phase of the transmitted
audio modulation.
8. Apparatus as claimed in any preceding
claim, further comprising means to set the
frequency of the carrier signal as high as is
115 compatible with reception of an adequate signal
by said second transducer.
9. Apparatus as claimed in Claim 3, wherein
said first transducer acts also as said reference
transmitting transducer; wherein said first
120 transducer, said second transducer and said first
reference receiving transducer are all located
substantially in the same plane and point towards
a surface the position of which is to be measured;
and wherein said reference distance between said
125 first reference receiving transducer and said first

transducer is measured along said plane.

10. Apparatus as claimed in Claim 1 and

substantially as hereinbefore described with reference to the accompanying drawings.